ELECTRIC CURRENT INDUCED AMPLIFICATION OF SLOW SURFACE PLASMON POLARITONS IN SEMICONDUCTOR-GRAPHENE-DIELECTRIC STRUCTURE

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- Surface waves propagating along the boundary between two media, one of which has a negative dielectric permittivity, are called **surface plasmon polaritons** (**SPP**s).
  SPPs are characterized by high field localization and penetrate in each adjacent medium at a depth of the wavelength order, decaying exponentially with the distance from the interface.

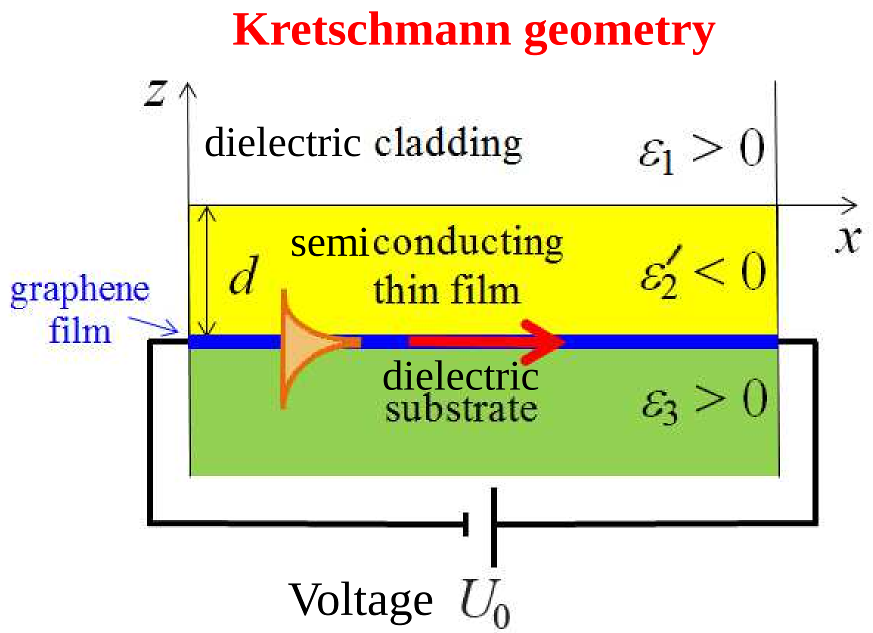
- The use of materials with negative permittivity (as a rule, conductive media) leads to ohmic loss. Therefore it is necessary to compensate for high loss.

- The loss compensation techniques, based on the optical-pump-generated induction of population inversion in the active medium located near the surface of the metal are characterized by low power efficiency, require an external laser, and only work in pulsed mode, which does not allow to count on their wide practical use.

- The alternative approach to the problem of increasing of the free path of SSPs is based on mechanism of <u>energy transfer</u> <u>from plasma oscillations</u> (dc current), <u>to SSPs</u> (electromagnetic waves).

- The evanescent electromagnetic wave amplification by dc electric current can be observed when the <u>phase velocity</u> of the SPP wave and the <u>charge drift velocity</u> are <u>comparable</u>.

- To obtain this **synchronism condition**, we suggest to use the **graphene** placed on the planar interface where the SPP propagates.



Permittivity of semiconducting film:

$$\varepsilon_2(\omega) \approx \varepsilon_\infty \left[1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \right] = \varepsilon_2' + i\varepsilon_2''$$

ω: angular frequency
ω_p : plasma frequency
γ: relaxation parameter

Red arrow: direction of the electron flux in the graphene under an applied voltage U_0 .

SPP propagation constant: $\beta = \beta' + i\beta''$
$\beta'' < 0$: damping of SPP

SPP dispersion equation:

$$\exp(-2q_2 d) = \frac{q_2\varepsilon_1 + q_1\varepsilon_2}{q_2\varepsilon_1 - q_1\varepsilon_2} \cdot \frac{q_2\varepsilon_3 + q_3\varepsilon_2}{q_2\varepsilon_3 - q_3\varepsilon_2}$$

$$q_j = \sqrt{\beta^2 - k_0^2 \varepsilon_j} \quad (j = 1, 2, 3)$$

$$k_0 = \omega / c$$

$$\frac{dE_x}{dx} + i\frac{\omega}{V_{ph}}E_x = -\frac{1}{2}\left(\frac{\omega}{V_{ph}}\right)^2 K\,I \quad (1)$$

interaction of SPP waves (electric field component E_x) with the drift conduction current (absolute value I)

$$K = \frac{4\pi V_{ph}^2}{\varepsilon_\infty(\omega^2 + \omega_p^2)V_g}\frac{|E_x|^2}{\int |E|^2\, dS}$$

coupling parameter

$$V_{ph} = \omega/\beta'$$

phase velocity of SPP

$$V_g = \left(\partial\beta'/\partial\omega\right)^{-1}_{\omega=\omega_0}$$

group velocity of SPP

Currents in graphene I_{gr} and semiconductor I_s : $\dfrac{I_s}{I_{gr}} \approx \dfrac{\mu_s n_s}{\mu_{gr} n_{gr} \beta'}$

$n_s \sim 10^{17}$ cm^{-3} : volume charge carriers concentration in semiconductor
$n_{gr} \sim 10^{12} \div 10^{14}$ cm^{-2}: surface charge carriers concentration in graphene
$\mu_{gr} = 2.5\cdot 10^5$ cm$^2\cdot$V$^{-1}\cdot$s^{-1} : charge mobility in graphene
$\mu_s << \mu_{gr}$: charge mobility in semiconductor

$$\frac{I_s}{I_{gr}} << 1$$

We can assume that the drift current is localized in graphene

Under the influence of the SPP wave field the amplitude of the current *I* becomes modulated along the length of the waveguide

$$\frac{d^2J}{dx^2}+2i\frac{\omega}{V_0}\frac{dJ}{dx}-\frac{1}{V_0^2}\left(\omega^2-\omega_q^2\right)J=i\frac{\omega}{V_0}\frac{I_0}{2U_0}E_x \quad (2)$$

equation for electric current and electromagnetic field in graphene

$J(x)=I(x)-I_0<<I_0$: small perturbations of the current amplitude

$V_0=\mu_{gr}U_0/l_x$: drift velocity of the charge carriers in graphene of lenth l_x

ω_q : reduced plasma frequency in graphene

Compatibility of Eq. (1) and (2)

$$(\omega-GV_{ph})\left[(\omega-GV_0)^2-\omega_q^2\right]=C^3\omega^3 \quad (3)$$

$$C=\left(\frac{KI_0}{4U_0}\frac{V_0}{V_{ph}}\right)^{1/3}\approx\left(\frac{\eta}{2}\frac{\omega_q^2}{\omega^2+\omega_p^2}\frac{V_{ph}}{V_g}\right)^{1/3}$$

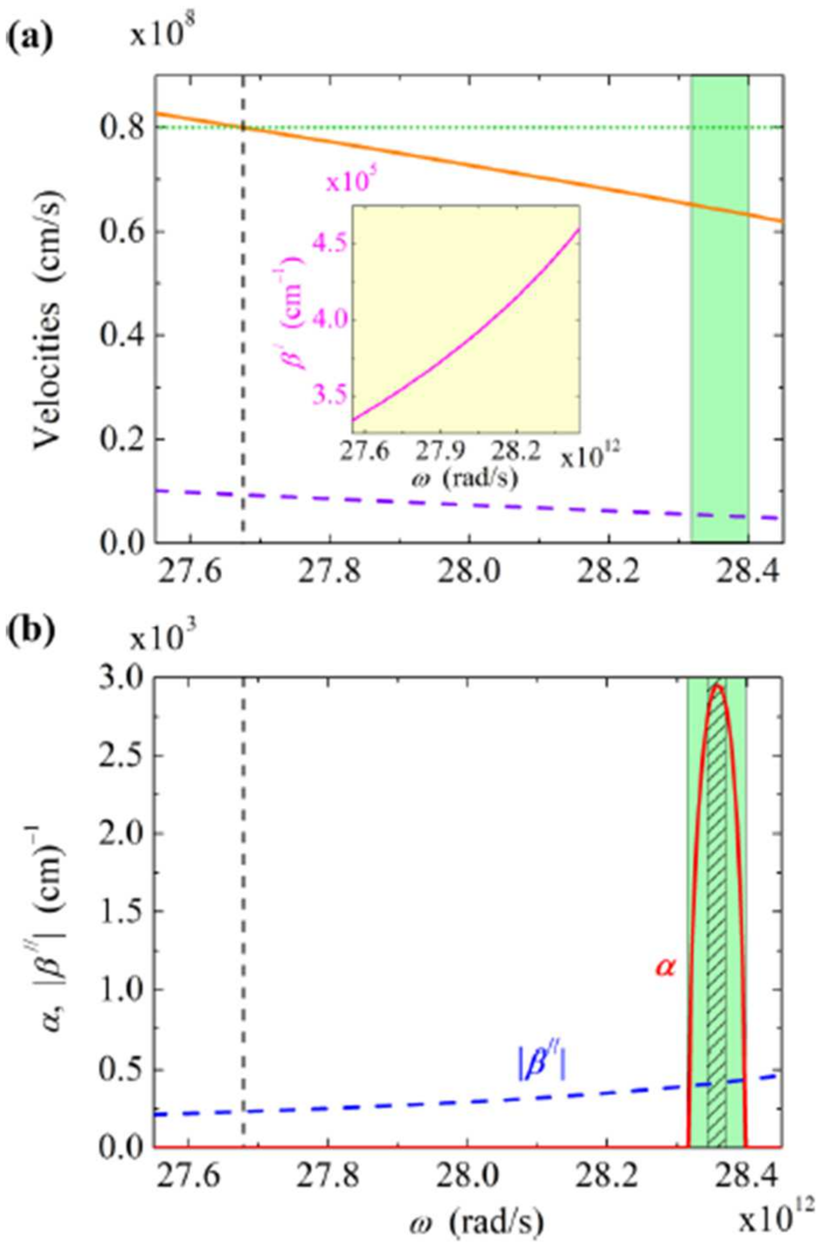
analog of Pierce parameter

$$\eta_{1,3}\approx\frac{\varepsilon_2'^2k_0^2}{\beta'^2(\varepsilon_2'+\varepsilon_{1,3})^2+\varepsilon_2'^2k_0^2}$$

Complex routs of Eq. (3)

SPP amplification coefficient:

$$\alpha=\left|\mathrm{Im}(G)\right|$$



Dispersion of the SPP parameters:

(a) inset : propagation constant $\beta^{/}$

phase velocity V_{ph} ,

group velocity V_g ,

drift velocity of charge carriers in graphene $V_0 = 0.8 \cdot 10^8$ cm·s^{-1}

(b) amplification coefficient α ,

loss coefficient $\beta^{//}$

In the green areas the amplification coefficient is larger than the absolute value of loss coefficient: $\alpha > | \beta^{//} |$.

Parameters:

$\varepsilon_\infty = 10.89$, $\omega_p = 3.42 \cdot 10^{13}\ s^{-1}$, $\gamma = 0.01 \cdot \omega_p$

$\varepsilon_1 = 1$, $\varepsilon_3 = 4$

$l_x = 200\ \mu m$, $d = 0.1\ \mu m$

$U_0 = 20\ V$

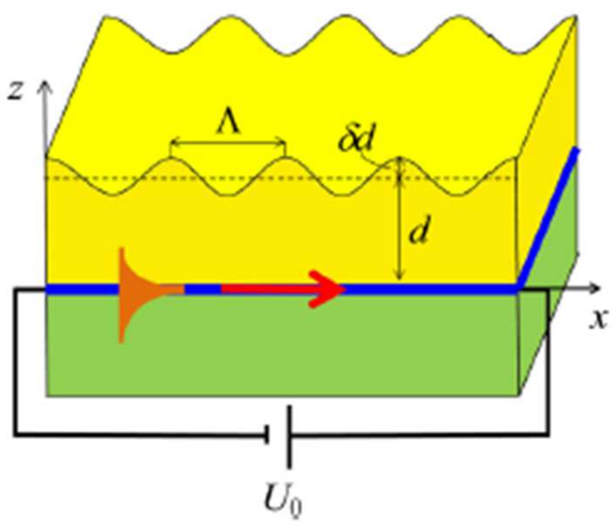
Slow SPPs: $\beta' >> k_0$

$\left(\beta' \sim 10^5\ \text{cm}^{-1},\ k_0 \sim 10^3\ \text{cm}^{-1}\right)$

Maximal SPP amplification coefficient:

$\boldsymbol{\alpha_{\max} = 3 \cdot 10^3\ \text{cm}^{-1}}$

Resonance amplification of surface plasmon polariton in a structure with distributed feedback



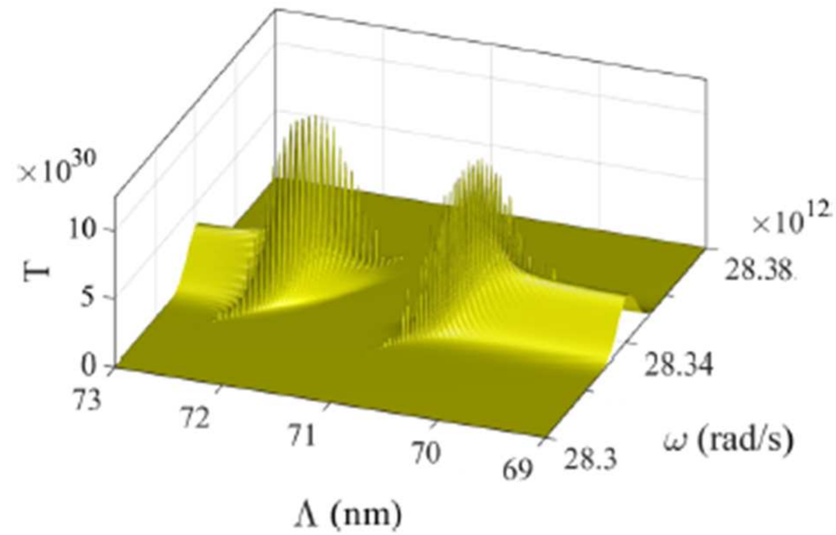


FIG. 3. Evolution of the transmission coefficient T with angular frequency ω of SPP and period of the structure Λ. The parameters of the structure are the same as for Fig. 2.

$$T = \left|\frac{A(L)}{A(0)}\right|^2 = \left|\frac{S\exp(\alpha L/2)}{(g - i\Delta\beta)\sinh(SL) - S\cosh(SL)}\right|^2$$

$$S^2 = \kappa^2 + (g - i\Delta\beta)^2$$

Conclusions

- ✓ We have investigated the interaction of slow plasmon polariton waves of far-infrared regime with an electric current induced in the graphene film deposited on the boundary between a semiconductor and dielectric.

- ✓ It is shown that under the synchronism condition, when phase velocity of a surface plasmon polariton approaches the drift velocity of charge carriers in graphene, a slow surface wave can be substantially enhanced by the drift current in graphene.

- ✓ This amplification can not only compensate for the natural damping of surface plasmon polaritons, but also can reach huge values which are orders of magnitude larger the ohmic loss.

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AMPLIFICATION OF SPIN WAVES BY DRIFT CURRENT

- Antiferromagnet
- *s-f* exchange amplification
- The acoustic branch of spin waves
- Longwave approximation
- The limit of frequent collisions
- The magnetic field is directed along the current carrier drift direction.

V. D. Lakhno, « Spin wave amplification in magnetically ordered crystals », Physics - Uspekhi **39**(7), 669-693 (1996).

Amplification of spin waves (acoustic branch) in a longitudinal field : parameters

$$v_s = gM_0\sqrt{2\delta_0(\alpha-\alpha_{12})\left(1-\frac{H^2}{H_c^2}\right)}$$

phase velocity of a spin wave;

H is applied field
H_c is a collapse field
here α, α_{12}, and δ_0 are exchange constants of antiferromagnet

$$g = 2\mu_0/\hbar,\ M_0 = 2\mu_0 S/a^3$$

$$\sqrt{\frac{\alpha-\alpha_{12}}{2\delta_0}} \sim a$$

μ_0 is Bohr magneton,
S is number of magnetic lattices of antiferromagnet,
a is lattice constant

Dimensionless amplification coefficient $\alpha(\omega)$:

$$\frac{kv_s}{\omega} = 1 + \mathrm{i}\alpha$$

k is a modulus of the wave vector of a spin wave, here α is amplification

$$\alpha(\omega) \sim -\frac{4\omega^3 a^3/v_s^3(v_0/v_s-1)Q\omega_R/\omega}{(\omega_R/\omega)^2(1+\omega^2/\omega_R\omega_D)^2+(v_0/v_s-1)^2},$$

$$Q = \frac{1}{32}\frac{A^2 S}{\hbar\omega}\frac{\varepsilon a}{e^2}\sqrt{1-\frac{H^2}{H_c^2}}.$$

A is s-f exchange constant,
e is electron change,
ε is dielectric permittivity of antiferromagnet
ω_R is the dielectric relaxation frequency
ω_D is the diffusion frequency

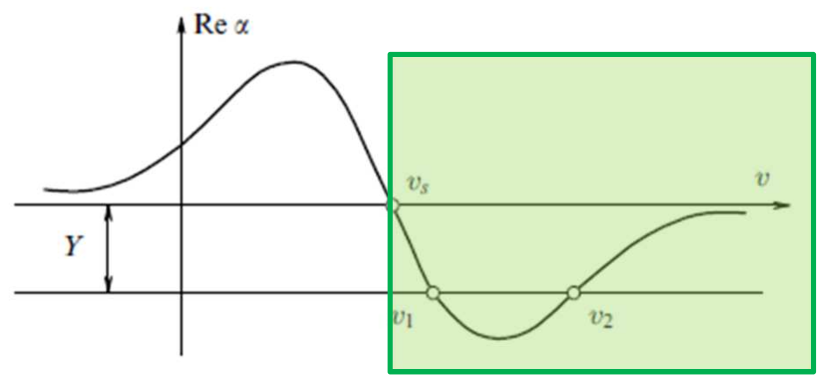


Figure 3. Spin wave amplification coefficient versus drift velocity of conduction electrons. The Re$\alpha(v)$ plot passes through zero for $v_0 = v_s$ ($Y = 0$) and $v_0 = v_1$ ($Y \neq 0$), where Y is the lattice absorption coefficient for spin waves (Section 3.4).

Amplification regime : drift current velocity v_0 is larger than the spin wave phase velocity v_s

Parameters :

$\omega^2 \sim 2\pi \cdot 50 \cdot 10^9$ rad$\cdot$s^{-1}
$\omega_R = 25 \cdot 10^{11}$ rad$\cdot$s^{-1} is the dielectric relaxation frequency % [10^8 - 10^{11}] s^{-1}
$\omega_D = 8 \cdot 10^{10}$ rad$\cdot$s^{-1} is the diffusion frequency % [10^7 - 10^{10}] s^{-1}

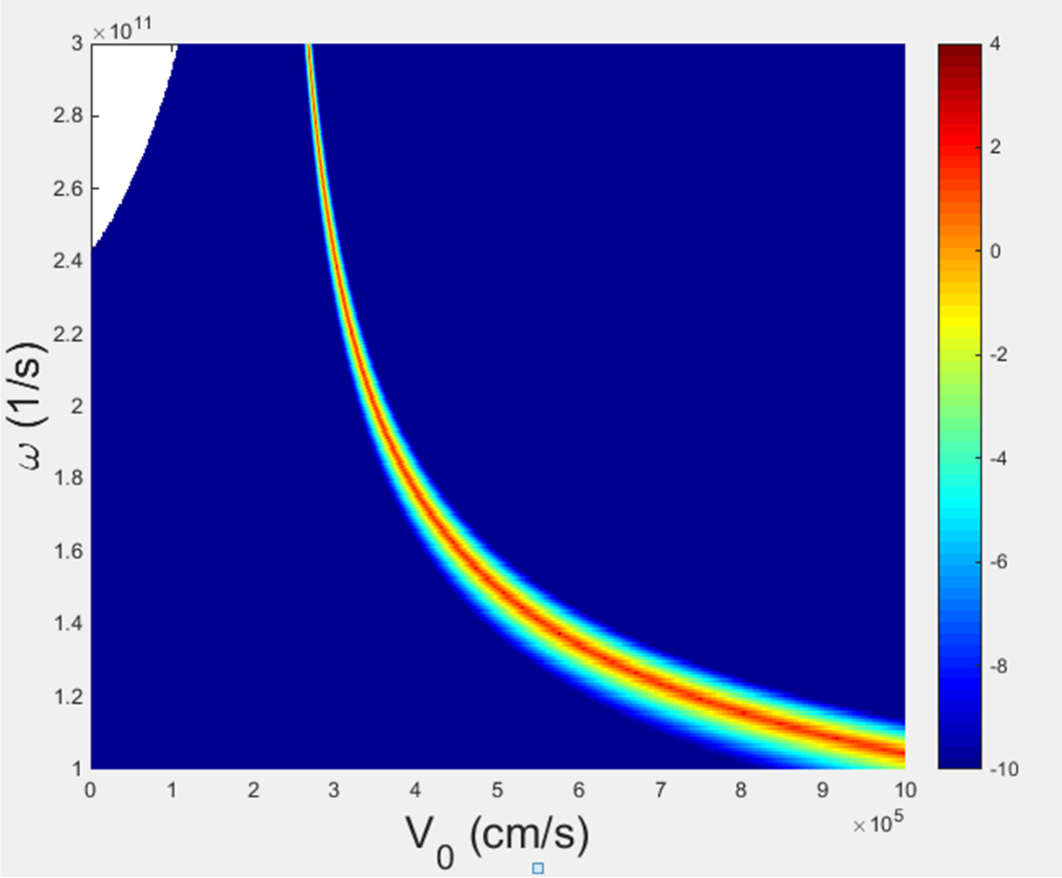
$$\omega^2 \sim \omega_R\, \omega_D$$

S = 2;
$a = 3 \cdot 10^{-8}$ cm
$\varepsilon = 20$: dielectric permittivity of antiferromagnet

$A = 0.5$ eV : s-f exchange constant
$\delta_0 = 100$;

$H = 0.1 \cdot 10^4$ G
$H_c = 10^4$ G

Distributed feedback structure :
thickness of the AFM film : 15·10^(-7) cm
change of the thickness : 0.1·h
Length of the AFM film : 10% of the SW wavelength corresponding to the minimal frequency of the chosen interval
Period of the thickness modulation of the thickness of the AFM film : 0.1 % of the SW wavelength corresponding to the minimal frequency of the chosen interval



Transmission coefficient of the spin wave (in logarithmic scale) as function of the drift velocity V_0 and the angular frequency ω. Here the phase velocity of the spin wave is $V_s \approx 2 \cdot 10^5$ cm/s.